Award Number: W81XWH-12-2-0042

TITLE: Development of Injury Thresholds Pertaining to Under-Body Blasts

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REPORT DATE: June 2012

TYPE OF REPORT: Annual

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT: Approved for Public Release;
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REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*
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1. REPORT DATE 01-06-2012	**2. REPORT TYPE** Annual		**3. DATES COVERED** 1 May 2012 - 31 May 2013
4. TITLE AND SUBTITLE Development of Injury Thresholds Pertaining to Under-Body Blasts			**5a. CONTRACT NUMBER**
			5b. GRANT NUMBER W81XWH-12-2-0042
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Robert S. Salzar			**5d. PROJECT NUMBER**
			5e. TASK NUMBER
E-Mail: salzar@virginia.edu			**5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Virginia Charlottesville, VA 22903-4833			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Medical Research and Materiel Command Fort Detrick, Maryland 21702-5012			**10. SPONSOR/MONITOR'S ACRONYM(S)**
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited			
13. SUPPLEMENTARY NOTES			
14. ABSTRACT Severe injuries are being reported from occupants of MRAP and other vehicles exposed to under-body blasts. Both the etiology of these injuries and an effective means to mitigate these injuries are not currently known or understood, although whole body accelerations and at least some limited seat-pan and toe-pan intrusions are expected. Furthermore, live-fire testing with the Hybrid-III instrumented crash test dummy has resulted in sensor data that is difficult to interpret due to the lack of this dummy's biofidelity in the blast range of loadings. This proposal teams the University of Virginia Center for Applied Biomechanics (UVA-CAB) with collaborators at the U.S. Army Aeromedical Laboratory (USAARL) to develop new, blast rate injury criteria applicable to those injuries typically seen in theater resulting from under-body blasts to vehicle occupants. These criteria will be used to develop injury criteria for the WIAMan blast test dummy, so that competing vehicle designs, interior injury mitigation strategies, and personal protective equipment can be evaluated using this test dummy. Preliminary testing of Hybrid-III has begun for comparison to live-fire and GenHull2 Hybrid-III response. Initial results show that the UVA ODYSSEY blast simulator represents well the UBB environment, and is sufficient for WIAMan development work.			
15. SUBJECT TERMS WIAMan, Lower Extremity, Pelvis, Thorax, Blast, Injury			

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** USAMRMC
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	14	**19b. TELEPHONE NUMBER** *(include area code)*

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Introduction

Severe lower extremity injuries are being reported from occupants of MRAP vehicles exposed to under-body blasts. Both the etiology of these injuries and an effective means to mitigate these injuries are not currently known or understood, although whole body accelerations and at least some limited toe-pan intrusion are expected. Furthermore, there is currently no objective test methodology to determine the risk of injury to the lower extremities due to foot-well intrusion from under-vehicle blast. The research that the University of Virginia's Center for Applied Biomechanics has undertaken aims to create injury criteria for such injuries as well as investigate the injury and response of vehicle occupants.

The research that is presently completed involves the design of an under-vehicle blast test device capable of testing both whole body PMHS and manikins over a range of expected loading environments. Extensive research into this loading environment has discovered broad spectrum loading with magnitudes ranging from 300g to 1800g, to over 68,000g. The current test device is designed to replicate each of these loading scenarios.

In addition, a primary injury mode has been identified that has not been previously known, or, well understood. This primary injury mode has appeared in the current military conflicts as a result of the increasing size of improvised explosive devices used to defeat the more fortified vehicle armor. This combination has resulted in a high frequency load to the lower extremity that is capable of producing injuries being reported from theater.

The following report outlines the details and results of the previous 60 days of research into understanding the environment and injuries suffered as a result of under-vehicle blasts.

1. Body

1.1 Underbody Blast Rig Design

The test specifications for UVA's test rig for simulating underbody blast were that the device should be able to simulate the primary effects of an underbody blast for a seated occupant. The blast simulator is designed to use the UVA SESA sled rails. The rig design contains both a toe pan and seat pan being driven by two-phased pneumatically driven impactors. Both the seat pan and toe pan are optimized to deliver as much of the blast energy as possible. A drawing of the whole design assembly is pictured in Figure 1.

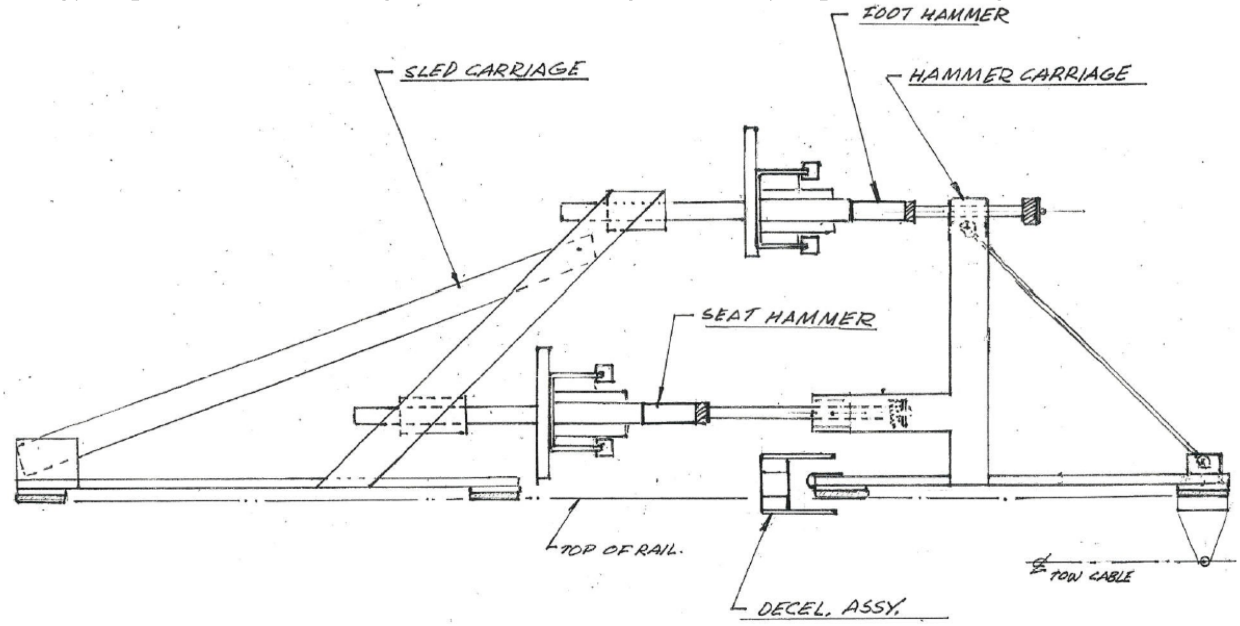

Figure 1: Blast Rig Schematic

The blast rig will produce an accelerative load on both the seat and toe pan based on data provided by the US Military. The accelerative loads can be controlled through a range of 500 g's with a rise time of 2ms, to 1800 g's with a rise time of 1.5 ms on both the seat and toe pan in the SAE-Z direction, with phasing between the toe and seat pan up to 10ms. The rig is designed to model both the positive and negative phase of acceleration while allowing a maximum intrusion (displacement) of 0.5 inches (12.7 mm) into the foot or pelvis, which was determined by double integrating the acceleration curves provided by the US Military. Figure 2 summarizes the acceleration range capabilities of the rig design.

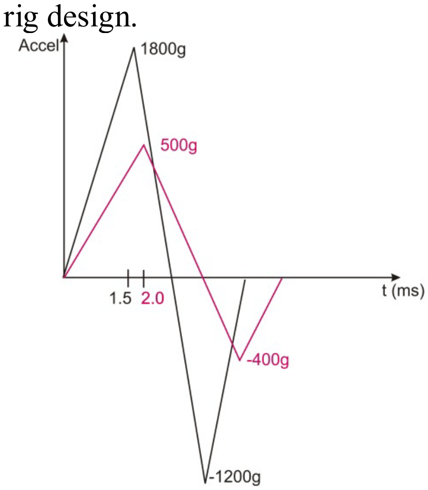

Figure 2. Range of expected toe-pan and seat-pan accelerations.

The structure of the rig consists of a carriage which uses guide pins on the seat and toe pans for size adjustment in order to fit a range of specimen sizes from 50th to 90th percentile males. The carriage also allows for an angle adjustment between the femur and tibia. Furthermore, the structure of the carriage was designed so that it would not interfere with the tracking of VICON markers which are used to track the kinematics of the body during a test. A drawing of the carriage assembly and base plate configuration are shown in Figures 3 and 4.

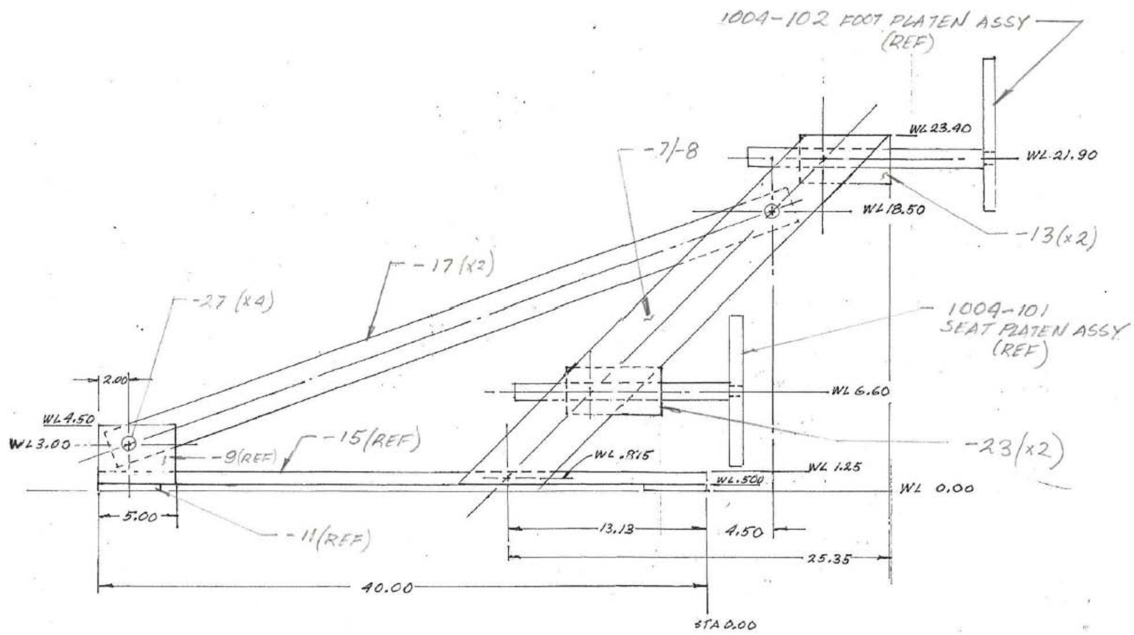

Figure 3: Carriage Assembly

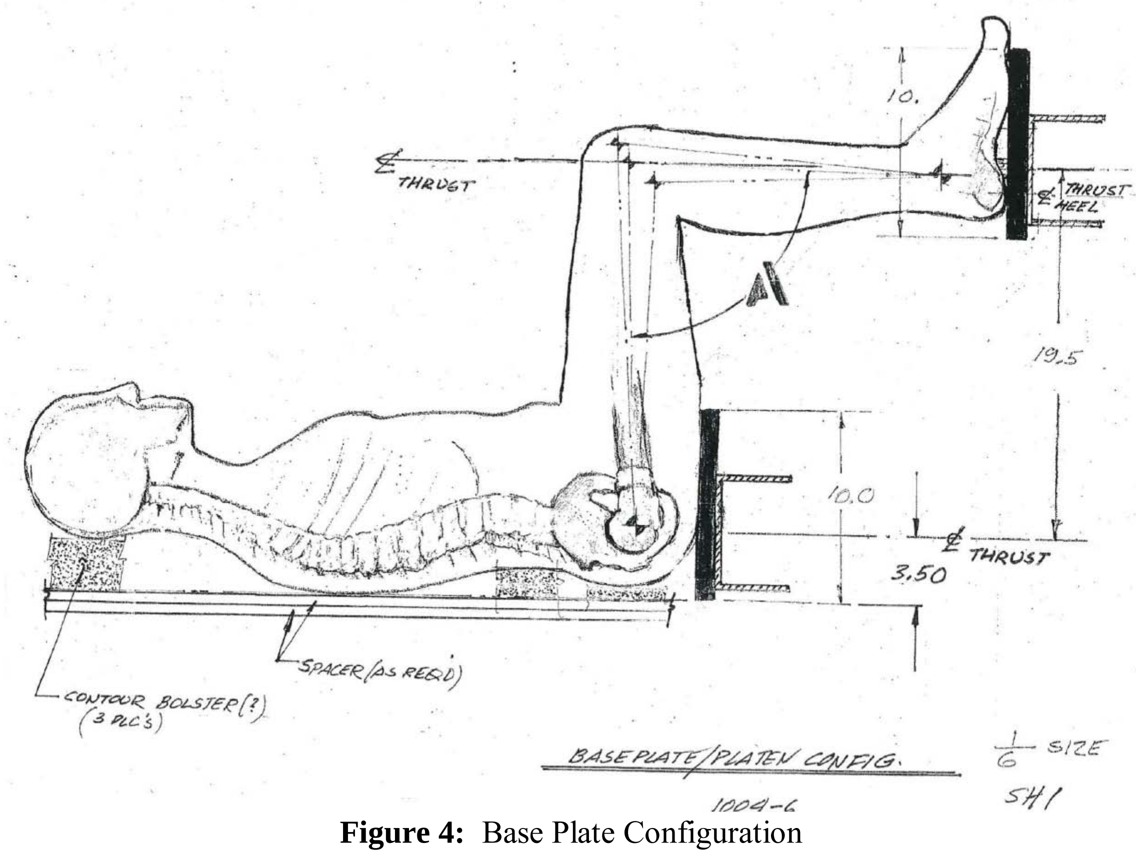

Figure 4: Base Plate Configuration

The rig is designed to deliver both the acceleration pulse discussed earlier as well as a high speed compression pulse from a smaller hammer. Therefore, a great amount of thought went into the design of the toe pan. Large hammers will be propelled into four 7-inch ultra high molecular weight polyethylene (UHMW) pulse shapers on both the toe and seat pan at velocities ranging from 22 to 45 feet per second. However, in order to create the high speed compression pulse, which we feel is the primary cause of injury in the lower extremities, two small "mini hammers" will hit the 1.5 square inch inserts which are positioned directly below the heel of each foot.

The timing of the "mini hammer" strike can be controlled so that it occurs just slightly before the impact of the main hammers. Drawings of the toe pan are shown in Figures 5 and 6.

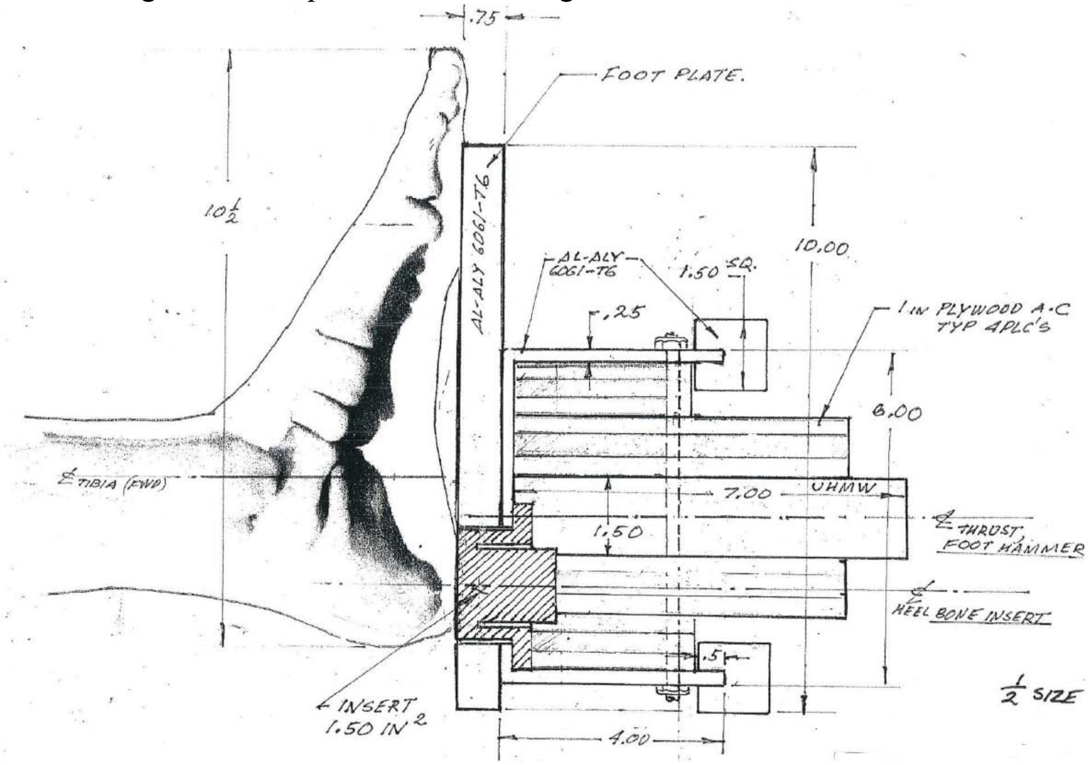

Figure 5: Side View of Toe Pan

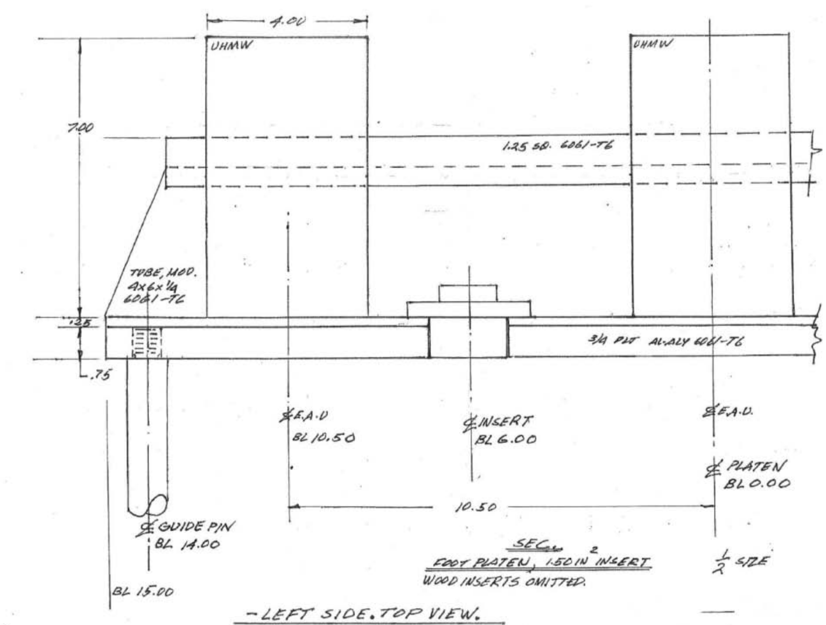

Figure 6: Left Side Top View of Toe Pan

1.2 Preliminary Hybrid-III Testing on ODYSSEY

The first four tests of ODYSSEY using an instrumented Hybrid-III dummy equipped with an instrumented Mil-LX have been performed and the analysis of the sensor data is ongoing. These results will be compared with the results of Hybrid-III tests performed by the US Army to ensure ODYSSEY is reproducing the environment seen in “live-fire” tests. Instrumentation used in the Hybrid-III tests is listed here in Table 1.

Table 1. Hybrid-III Test Instrumentation

CHANNEL COUNT	MEASURAND	SEN.	SEN. Type	AXIS	MAX	UNIT	CHANNEL COUNT
1	Acceleration	Right hindfoot	**TYPE**	X	2000	G	Cube 1, TDAS
2	Acceleration		7270	Z	6000	G	HI-T
3	Angular rate		8k ARS	X	8k	Deg/s	TDAS
4	Angular rate		18k ARS	Y	18k	Deg/s	HI-T
5	Acceleration	Left hindfoot	7264B	X	2000	G	Cube 1, TDAS
6	Acceleration		7270	Z	6000	G	HI-T
7	Angular rate		8k ARS	X	8k	Deg/s	TDAS
8	Angular rate		18k ARS	Y	18k	Deg/s	HI-T
9	Acceleration	Right Distal Tibia	7264B	X	2000	G	Cube 1, TDAS
10	Acceleration		7270	Z	6000	G	HI-T
11	Angular rate		8k ARS	X	8k	Deg/s	TDAS
12	Angular rate		18k ARS	Y	18k	Deg/s	HI-T
13	Acceleration	Left Distal Tibia	7264B	X	2000	G	Cube 1, TDAS
14	Acceleration		7270	Z	6000	G	HI-T
15	Angular rate		8k ARS	X	8k	Deg/s	TDAS
16	Angular rate		18k ARS	Y	18k	Deg/s	HI-T
17	Acceleration	Hybrid-III Head CG	7264B	X	2000	G	Cube 2, TDAS
18	Acceleration		7264B	Z	2000	G	TDAS
19	Angular rate		8k ARS	X	8k	Deg/s	TDAS
20	Angular rate		8k ARS	Y	8k	Deg/s	TDAS
21	Acceleration	Hybrid-III T1	7264B	X	2000	G	Cube 2, TDAS
22	Acceleration		7264B	Z	2000	G	TDAS
23	Angular rate		8k ARS	X	8k	Deg/s	TDAS
24	Angular rate		8k ARS	Y	8k	Deg/s	TDAS
25	Acceleration	Hybrid-III Pelvis	7264B	X	2000	G	Cube 2, TDAS
26	Acceleration		7264B	Z	2000	G	HI-T
27	Angular rate		8k ARS	X	8k	Deg/s	TDAS
28	Angular rate		8k ARS	Y	8k	Deg/s	HI-T
29	Acceleration	Toe pan	7270	Z	6000	G	HI-T
30	Acceleration	Seat pan	7270	Z	6000	G	HI-T
31	Belt tension load	Left				N	TDAS

		shoulder belt					
32	Belt tension load	Right shoulder belt				N	TDAS
33	Belt tension load	Lap belt				N	TDAS
34-39	Forces/moments	Hybrid-III lumbar spine	Den1842	XYZ		N, Nm	TDAS
40-45	Forces/moments	Hybrid-III Right Femur	Den1914	XYZ		N, Nm	Fx+My=HI-T, TDAS
46-51	Forces/moments	Hybrid-III Left Femur	Den1914	XYZ		N, Nm	Fx+My=HI-T, TDAS
52-57	Forces/moments	Hybrid-III Right Upper Tibia	Den3785J	XYZ		N, Nm	Fz+My=HI-T, TDAS
57-62	Forces/moments	Hybrid-III Left Upper Tibia	Den3785J	XYZ		N, Nm	Fz+My=HI-T, TDAS
63-68	Forces/moments	Hybrid-III Right Lower Tibia	Den3785J	XYZ		N, Nm	Fz+My=HI-T, TDAS
69-74	Forces/moments	Hybrid-III Left Lower Tibia	Den3785J	XYZ		N, Nm	Fz+My=HI-T, TDAS
75-80	Forces/moments	Hybrid-III Upper Neck	Den1716A	XYZ		N, Nm	TDAS
81-86	Forces/moments	Hybrid-III Lower Neck	FTSS210	XYZ		N, Nm	TDAS

Data acquisition for these tests used a combination of DTS-TDAS-Pro and Hi-Techniques Synergy. High speed video was obtained for each test focused on the overall lateral kinematics of the Hybrid-III under simulated UBB loadings, and focused on the foot-plate and seat-plate interaction with the Hybrid-III. The test matrix for these preliminary Hybrid-III tests is shown in Table 2. The goal of these preliminary tests is to identify the range of subinjurious impact accelerations required to execute Jumpstart Task 1.

Table 2. Poseidon 2 Test Matrix

Test	Sled Pressure	Hammer Velocity	Foot Hammer Mass	Seat Hammer Mass	Total Hammer Mass	Max Foot Plate Accel	Max Seat Plate Accel	Max Lower Tibia Fz
	(kPa)	(m/s)	(kg)	(kg)	(kg)	(g)	(g)	(N)
2.1	132	8.6	32.4	68.6	142.1	190.2	NA	-5025
2.2	133	8.7	32.4	68.6	142.1	165.1	NA	-3651

2.3	104	7.1	32.4	68.6	142.1	135.4	NA	-2831
2.4	188	11.1	32.4	68.6	142.1	230.0	433.5	-4951

The overall occupant setup is shown in Figure 7. Focus on the foot plate (Figure 8) and seat plate (Figure 9) interaction is also shown.

Figure 7. ODYSSEY with instrumented Hybrid-III onboard.

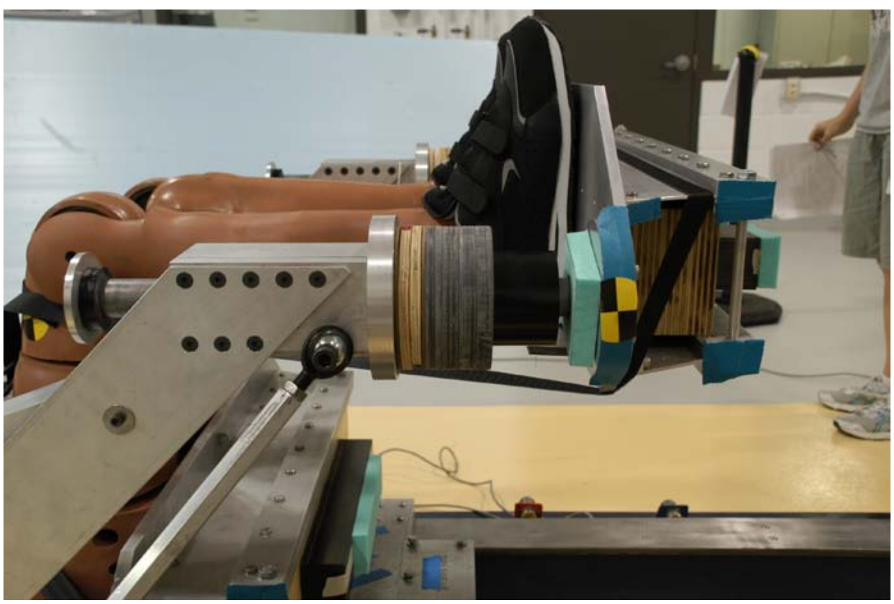

Figure 8. Foot placement on foot plate assembly.

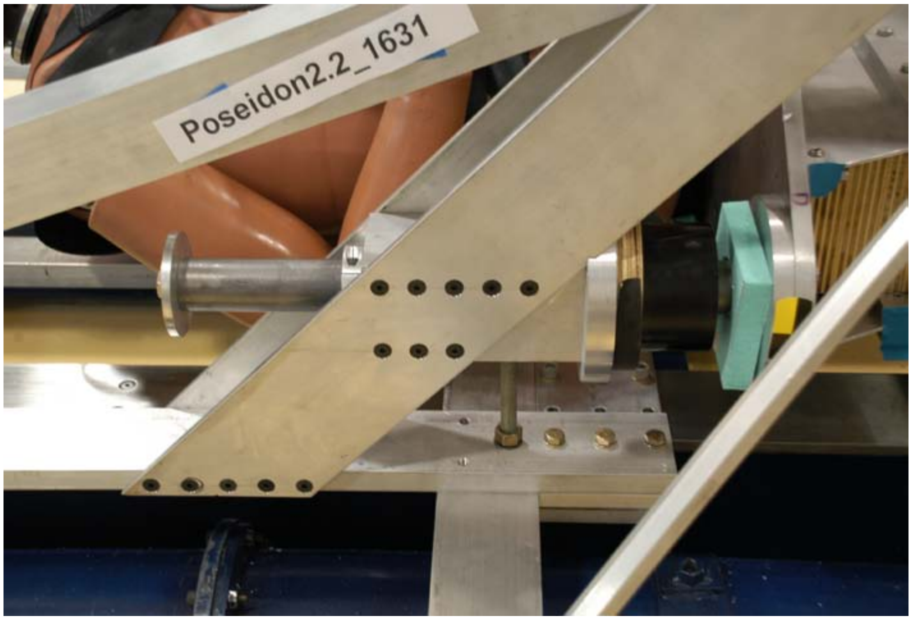

Figure 9. Seat placement on seat plate assembly.

1.3 Results

The following results are plotted for demonstration purposes, but do not indicate finalized results. These plots are subject to further analysis. These plots are results from the first series of Hybrid-III tests on ODESEEY and are in the SAE-coordinate system, and filtered using SAE J211 filtering standards.

1.3 Results

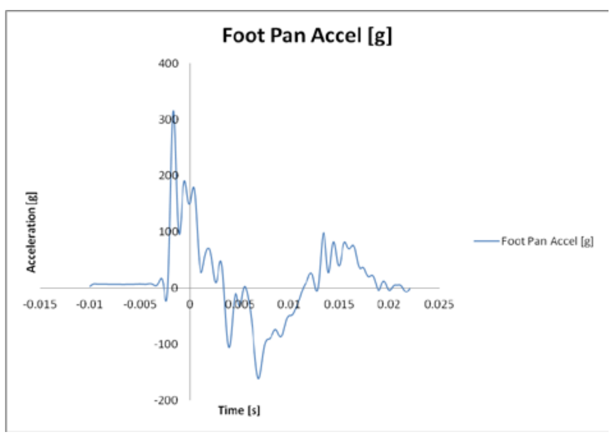

Figure 10. Foot plate acceleration (Test 2.1) Vertical Axis is Accel (g), Horizontal Axis is Time in (s).

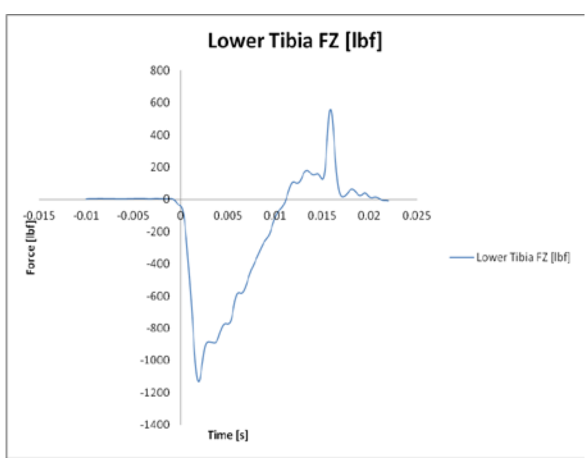

Figure 11. Lower tibia force (Fz) (Test 2.1). Vertical Axis is Force (lbf), Horizontal Axis is Time in (s).

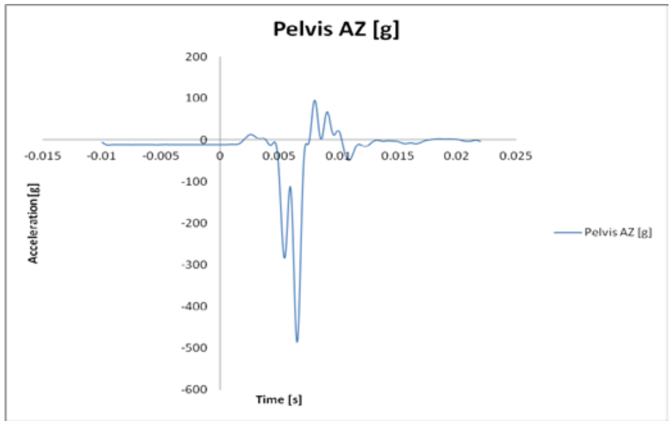

Figure 12. Pelvis acceleration (Test 2.1). Vertical Axis is Accel (g), Horizontal Axis is Time in (s).

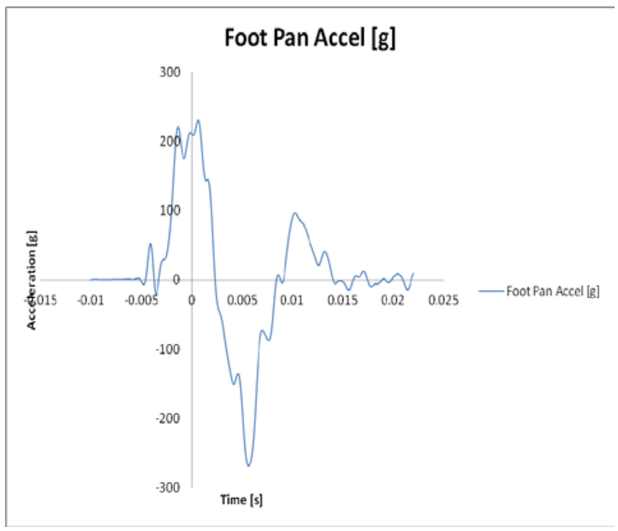

Figure 13. Foot plate acceleration (Test 2.4) Vertical Axis is Accel (g), Horizontal Axis is Time in (s).

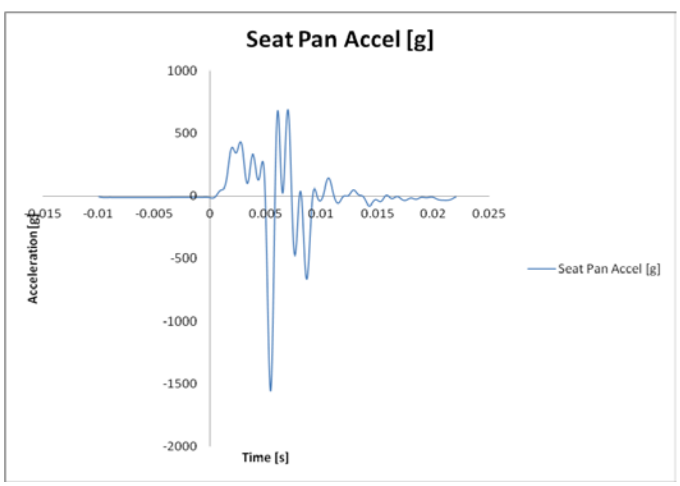

Figure 14. Seat plate acceleration (Test 2.4) Vertical Axis is Accel (g), Horizontal Axis is Time in (s).

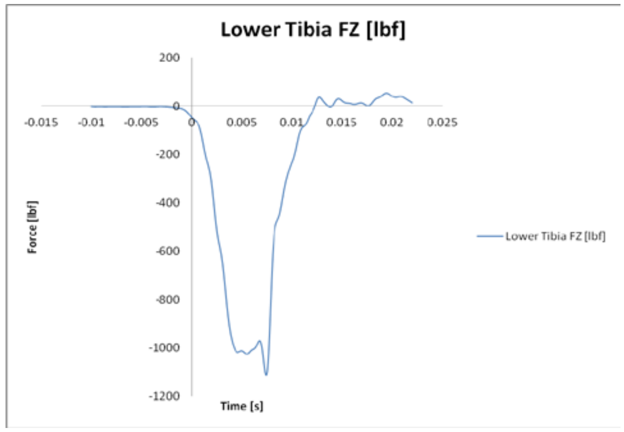

Figure 15. Lower tibia force (Fz) (Test 2.4). Vertical Axis is Force (lbf), Horizontal Axis is Time in (s).

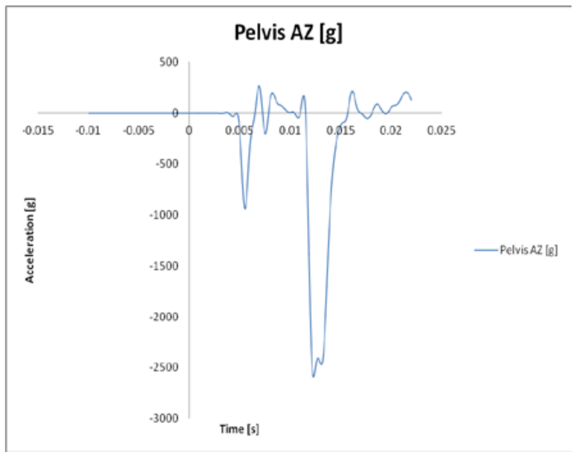

Figure 16. Pelvis acceleration (Test 2.4). Vertical Axis is Accel (g), Horizontal Axis is Time in (s).

Purchases
Initial purchases that have not hit the contract include the procurement of multiple whole body PMHS and component parts from approved Army vendors. In addition, the high-speed x-ray system is in the ordering process.

Key Research Accomplishments

- Finalized blast rig design to include experimental evidence of the existence of suggested injury mechanism
- First instrumented Hybrid-III tests with and without Mil-LX for comparison of ODYSSEY with Live-Fire and GenHull2 results (comparison yet to be completed).
- Completion of cadaveric testing approvals (pending approval letter)
- Finite element proof of concept for injury mechanism
- Paper and presentation to the Society of Experimental Mechanics (SEM) XII International Congress & Exposition on Experimental & Applied Mechanics: Bailey, AM, Boruah, S, Christopher, JJ, Bennett, BC, Shafieian M, Cronin, DS, Salzar, RS (2012) "Injury Potential of Shock Induced Compressive Waves on Human Bone" 2012 SEM International Congress, Costa Mesa, CA.

Reportable Outcomes

- A robust, repeatable blast simulator capable of accelerations up to 1800g in less than 1.5 ms is possible for laboratory simulation of underbody blast.
- Preliminary Hybrid-III tests for comparison with previous live-fire and other tests for cross-platform comparison.

Conclusion

Though only in the first 60 days of this 5 year contract, all preliminary steps have been completed allowing the forward progress of this research to begin upon acceptance of the individual task's test protocols. The design of test fixtures for each task has begun, as has the search for appropriate PMHS specimens from Army approved sources.